THE RHEOLOGICAL CHARACTERISTICS OF A SAND-ASPHALT MIXTURE

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BY

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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Technical Paper

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A SAND-ASPHALT MIXTURE

TO: K. B. Woods, Director
Joint Highway Research Project

January 29, 1959

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project

File: 2-4-15
Project: C-36-6M

Attached is a paper entitled, "The Rheological Characteristics of a Sand-Asphalt Mixture." This paper has been prepared by Professors L. E. Wood and W. H. Goetz of our staff for presentation at the Annual Meeting of the Association of Asphalt Paving Technologists in Denver, Colorado, in January, 1959.

The paper is presented for the record.

Respectfully submitted,

H. L. Michael

H. L. Michael, Secretary

HLM:ac

Attachment

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Purdue University
Lafayette, Indiana

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THE RHEOLOGICAL CHARACTERISTICS OF A SAND-ASPHALT MIXTURE

L. E. Wood and W. H. Goetz

INTRODUCTION

Much time and effort has been spent developing mechanical models that would duplicate the action of bitumens when under load. These bitumens behave, in general, as visco-elastic materials. Two early investigators, Saal (1) and Lethersich (2) in describing the behavior of bitumens under load made use of mechanical models that were composed of two springs and two dashpots but in different arrangements. Van der Poel (3) pointed out -- "Quantitative correlation of their results is difficult as it is possible to represent a deformation curve, obtained from measurements, equally well by various models.---Another difficulty is that models with a finite number of elements fail to give a representative picture over a sufficiently large range of loading times and frequencies."

Saal (1) and Pfeiffer (4) both reported that the deformation pattern of a bitumen under load consisted of instantaneous elastic strain, retarded elastic strain, and viscous flow. When the load is removed from a sample, immediate rebound can be observed followed by a retarded rebound. The recovery curve should follow the same function of time as the creep curve. A qualitative description of this behavior can be obtained by using a Burgers model which consists of an elastic component and a viscous component connected in series with an element made up of a viscous and an elastic component connected in parallel.

Brown and Sparks (5), in a recent paper, utilized a mechanical model that consisted of four Kelvin units along with a Maxwell unit to analyze the action of a penetration grade paving asphalt when under load. They obtained an excellent correlation between the characteristics of this

model and the behavior of the asphalt when subjected to stress. Studies of this type are quite valuable and more effort should be directed in this field. A more fundamental approach to the action of bitumens under load can be obtained in this manner, and, as Brown stated, "the student of practical asphalt application may foresee the day when improved asphalts of a much wider range of rheological properties may be hand-tailored to specific requirements from the materials supplied by nature."

In an attempt to describe the flow properties of bituminous mixtures, Mack (6) recommended dividing the deformation of a bituminous mixture under load into two parts - a recoverable and a non-recoverable part as suggested by a Burgers model. In Mack's study, no attempt was made to determine the constants of the various elements in the Burgers model. In a later study Mack (7) divided the deformation into the following three parts:

1) An instantaneous elastic strain independent of time.

2) A retarded elastic strain which is a function of time.

3) A plastic strain whose rate decreases with time.

In this study Mack was primarily concerned with a strength evaluation of bituminous mixtures. The deformation of a bituminous specimen under the action of a static load was used in determining this strength evaluation.

The investigation being reported in this paper initially was conceived to use a Burgers model analysis on the data collected by loading a bituminous specimen with a static load. This analysis became rather complex and the parameters of the components of the Burgers model seemed to have little physical significance when associatied with properties of bituminous mixtures contributed by asphalt or aggregate. It was decided to analyze the data collected on the basis of the plastic or viscous deformation-time relationship for the applied loads and the rebound associated with the removal of the applied load.

MATFRIALS

The sand used in this study was a river terrace material of glacial origin which met the gradation limits as set forth in ASTM D978-54, "Standard Specifications for Asphaltic Mixtures for Sheet Asphalt Paving," Surface Course Grading No. 2 (8). The sieve analysis of the sand is presented in Table 1 and depicted graphically in Figure 1. The control of the gradation was obtained by drying the sand, sieving it into respective sizes and recombining it by weight in the desired proportions as shown in Table 1. The material passing the No. 200 sieve was supplied by adding pulverized limestone.

The asphalt cement was supplied by the Texas Company at Port Neches, Texas. The physical properties of the asphalt cement are presented in Table 2. The viscosity values were obtained by means of a sliding-plate microviscometer.

The asphalt content for the sand-asphalt mixture was 9 per cent by weight of the total mixture. This value was chosen by using the Hubbard-Field design procedure.

TABLE 1

Sieve Analysis

Sieve		Per cent by Weight
Passing	Retained	
No. 4	No. 8	0
No. 8	No. 16	7
No. 16	No. 50	34
No. 50	No. 100	27
No. 100	No. 200	15
No. 200		17

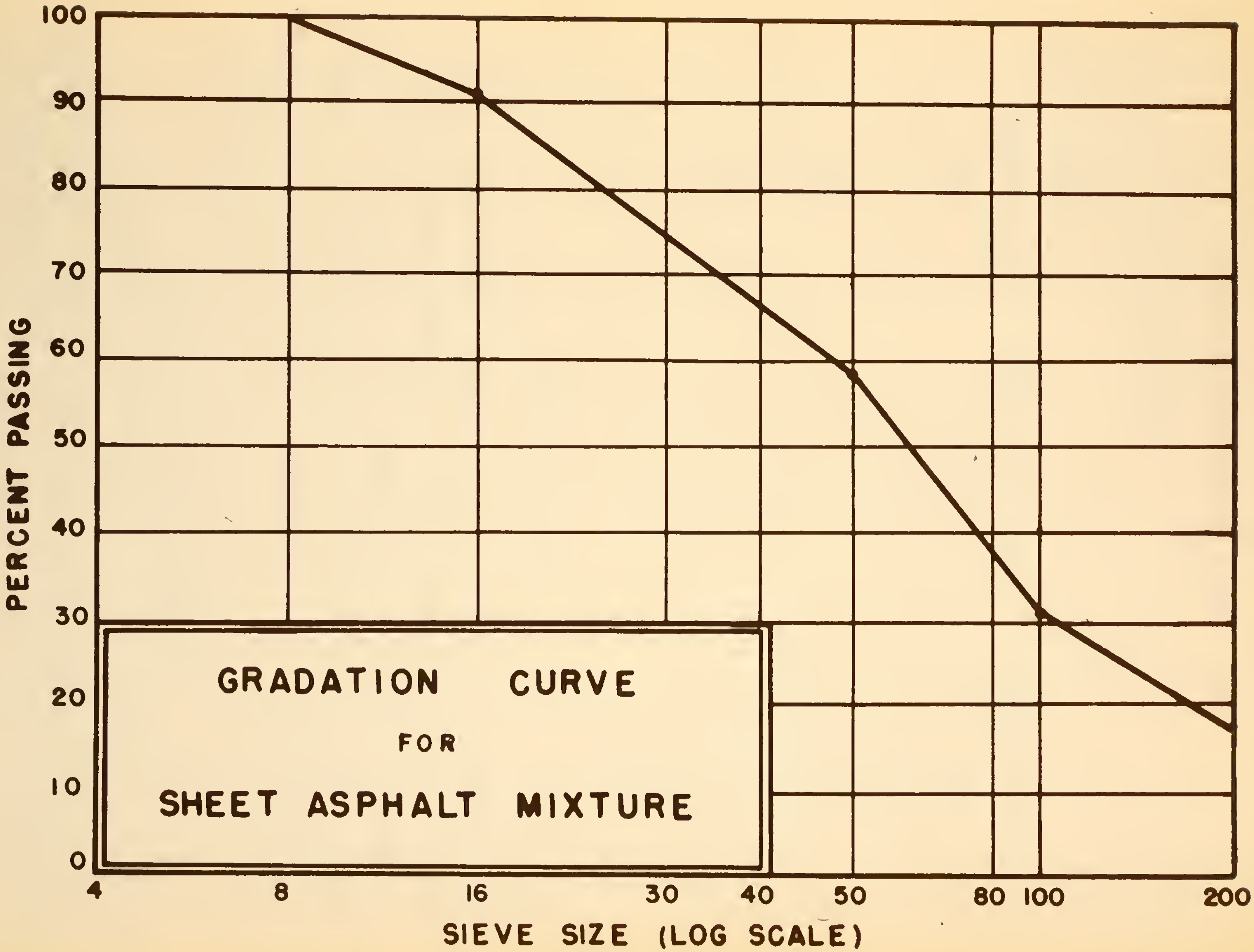
GRADATION CURVE
FOR
SHEET ASPHALT MIXTURE
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
4
8
16
30
40
50
80
100
200
SIEVE SIZE (LOG SCALE)

FIGURE 1

TABLE 2

Physical Properties of the Asphalt Cement

Penetration, 77°F, 100 gms, 5 sec.	66
Softening Point, °F	125

Viscosity Data:

Temperature, °F	Shear Rate, $sec.^{-1}$	Viscosity, poises
40	9.6×10^{-4}	9.0×10^{8}
	2.4×10^{-3}	8.1×10^{8}
	1.6×10^{-3}	2.1×10^{5}
100	8.2×10^{-2}	2.0×10^{5}
	5.4×10^{-1}	1.7×10^{5}
140	5.9×10^{-3}	5.1×10^{3}
	3.7×10^{-2}	4.2×10^{3}
	1.8×10^{-1}	4.0×10^{3}

TESTING PROCEDURES

Since a bituminous mixture can be classified as a visco-elastic material, it would be desirable to choose a method of evaluation that would permit one to determine both the elastic and viscous properties of the mixture. By observing the deformation as a function of time at a constant stress, it is possible to divide this deformation into a plastic and an elastic component.

Absolute Viscosity Determination

The sliding-plate microviscometer used in this study was a Hallikainen Model 1113A made available to the authors by the generous cooperation of the K. E. McConnaughay Asphalt Laboratory, Lafayette, Indiana. In preparing the

asphalt film on the glass plates, the asphalt cement was heated to approximately $300^{\circ}F$, which was the same temperature used in liquifying the asphalt for preparing the sand-asphalt specimens. The heated asphalt was placed on clean, glass plates and worked into a uniform layer with a thickness of approximately 50 microns. The prepared plates were cooled for one hour before being tested. For further information regarding viscosity determinations by means of a sliding-plate microviscometer, the reader is directed to a paper authored by Griffin, Miles, Penthes, and Simpson (9).

Static Load Test

The mixture used in this study was one in which the aggregate and asphalt were heated separately and then combined in a mixing operation. The aggregate was heated in an electric oven to a temperature of $325^{\circ}F$. The asphalt was heated in a gas oven to a temperature of $300^{\circ}F$.

The two constituents were mixed by hand in a heated porcelain bowl using a metal spoon for a period of two minutes and then molded into a specimen 2 inches in diameter by 4 inches in height by a double-plunger compaction method which included rodding the mixture into the mold. To control density of the specimens, care was taken to introduce a predetermined amount of material into the mold for compaction to the fixed height. The specimens were cured for two days in laboratory air at a temperature of $75 \pm 5^{\circ}F$. The height, diameter, and weight of the specimens were then obtained for bulk density calculations.

The static-load test was devised to obtain the relationship among the following variables: applied stress, temperature, strain, and time. The following temperatures were used: 40, 55, 70, 100, and $140^{\circ}F$. Before testing, the specimens were maintained at the test temperature for 30 minutes. These temperatures were maintained by means of a water bath. The static load was applied by a Soiltest consolidation apparatus.

The water bath containing the test specimen was centered in the consolidation frame. Ames dials were attached so that the deformation during loading and the rebound after the load was removed could be observed. The test set-up is shown in Figure 2. A small seating load was applied to the specimen (approximately 1 psi). The deformation dials were zeroed. The static load was placed on the specimen at time zero and the stop watch started. The deformation was recorded at 5, 20, 40, 60, and 100 seconds and every additional 100 seconds until the test was halted and the load removed.

The criterion for halting the test was the ability or the inability of the specimens to withstand the applied load. A specimen withstood the applied load if the deformation increased only 0.001 inches per 100 seconds for 400 seconds. A specimen failed to withstand the applied load when the deformation rate per unit time increased rather than decreased. When the deformation rate per unit time increased it was noted that complete failure of the test specimen was imminent.

The specimen rebound upon removal of the test load was followed and deformation values were recorded at fixed time intervals until essentially all of the rebound had occurred.

RESULTS

In the first phase of this investigation, the absolute viscosity of the asphalt cement was determined at a low shear rate and at various temperatures. In the second phase of this study, the deformation - time relationships of the sand-asphalt mixture were determined for various applied loads and temperatures.

Absolute Viscosity Determination

The results of the viscosity tests on the asphalt cement are presented in Table 2 and depicted graphically in Figure 3 where the log of the

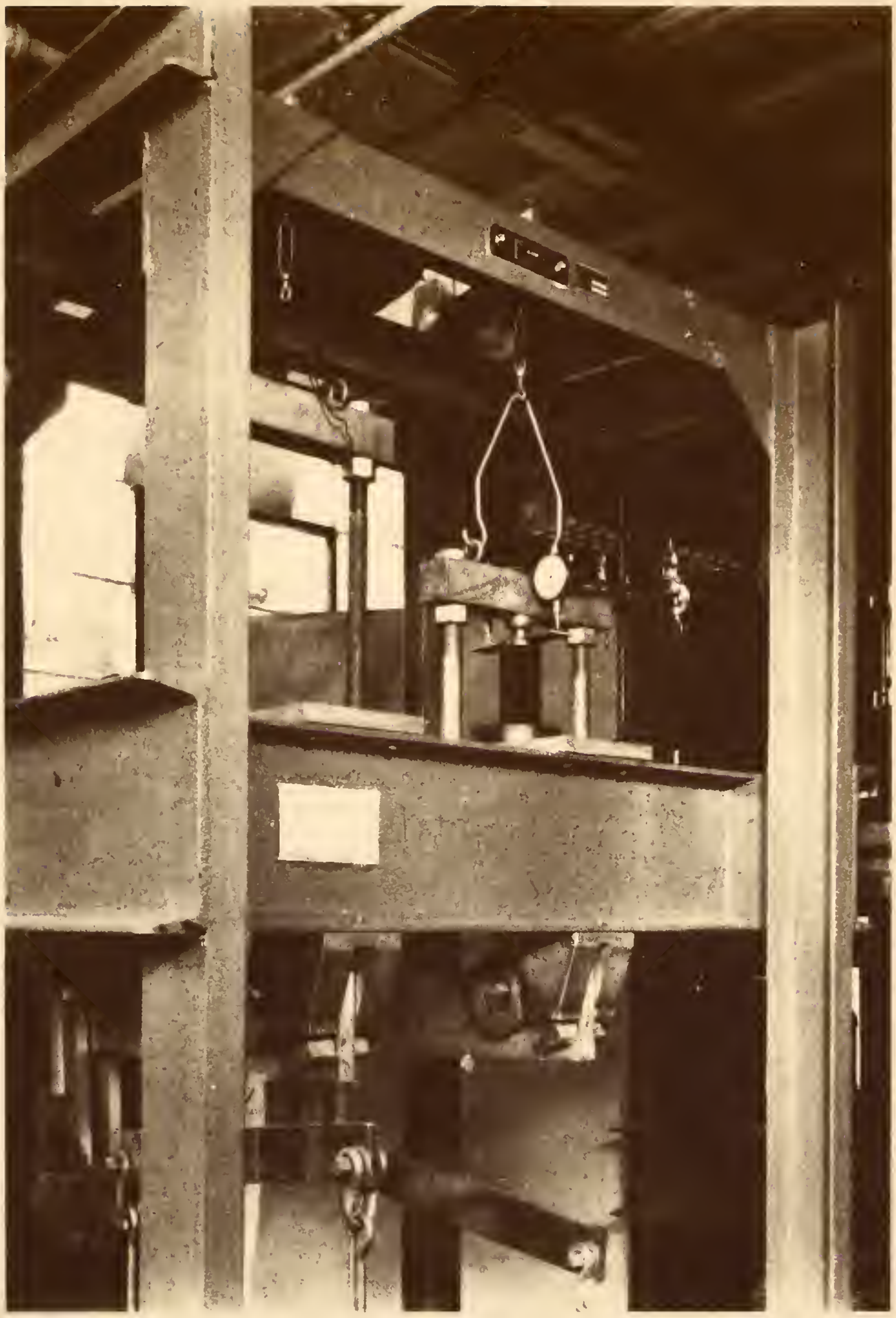

FIGURE 2 GENERAL VIEW OF THE STATIC LOAD APPARATUS READY FOR TEST (WITHOUT WATER BATH)

viscosity expressed in posises is plotted against the log of the shear rate expressed in reciprocal seconds. From Figure 3 the viscosity of the asphalt cement at a shear rate of 1×10^{-3} sec. $^{-1}$ was extrapolated for the various temperatures. These viscosity values are presented in Table 3. This low shear rate was chosen to obtain a comparison between the viscosity of the asphalt cement and the viscosity of the sand-asphalt mixture at comparable rates of shear.

TABLE 3

Viscosity Information on the Asphalt Cement

Temperature, °F	Shear Rate, sec. $^{-1}$	Viscosity, poises
40	1×10^{-3}	8.8×10^{8}
100	1×10^{-3}	2.4×10^{5}
140	1×10^{-3}	5.4×10^{3}

The temperature-viscosity data from Table 3 for the asphalt cement used in this investigation may be shown by plotting the log log viscosity in poises versus temperature in degrees Fahrenheit (see Figure 10). The slope of this plot may be used as a measure of temperature susceptibility of the asphalt.

Static Load Tests

The results of the static-load tests conducted on the sand-asphalt mixture at different temperatures are shown graphically in Figures 4, 5, 6, 7, and 8 where the deformation in inches is plotted against the time in seconds for various applied loads.

In all of the static-load tests there is a similar pattern between deformation and time. Upon application of the load there is an instantaneous

RELATIONSHIP BETWEEN VISCOSITY OF ASPHALT AND SHEAR RATE AT VARIOUS TEMPERATURES

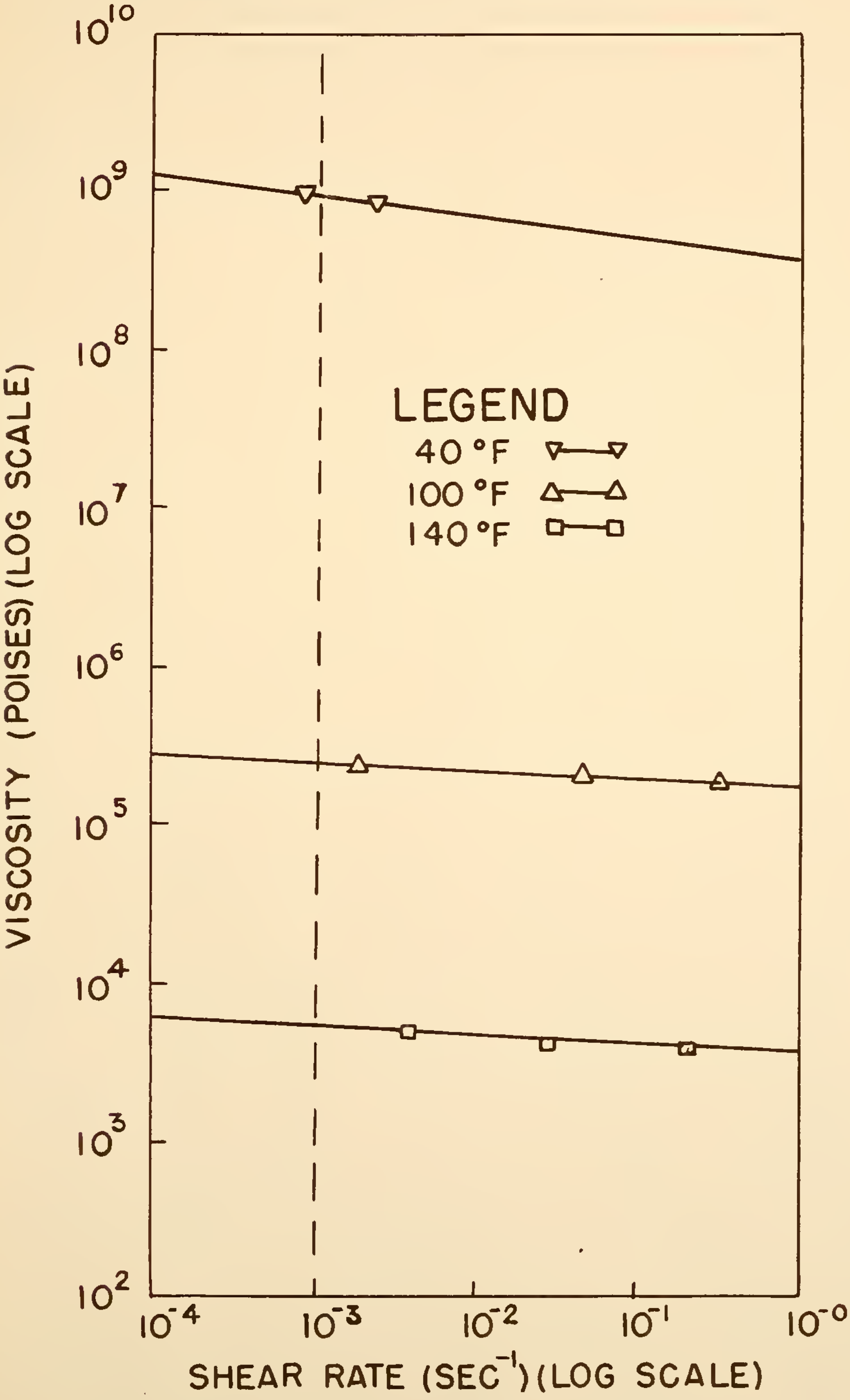

FIGURE 3

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

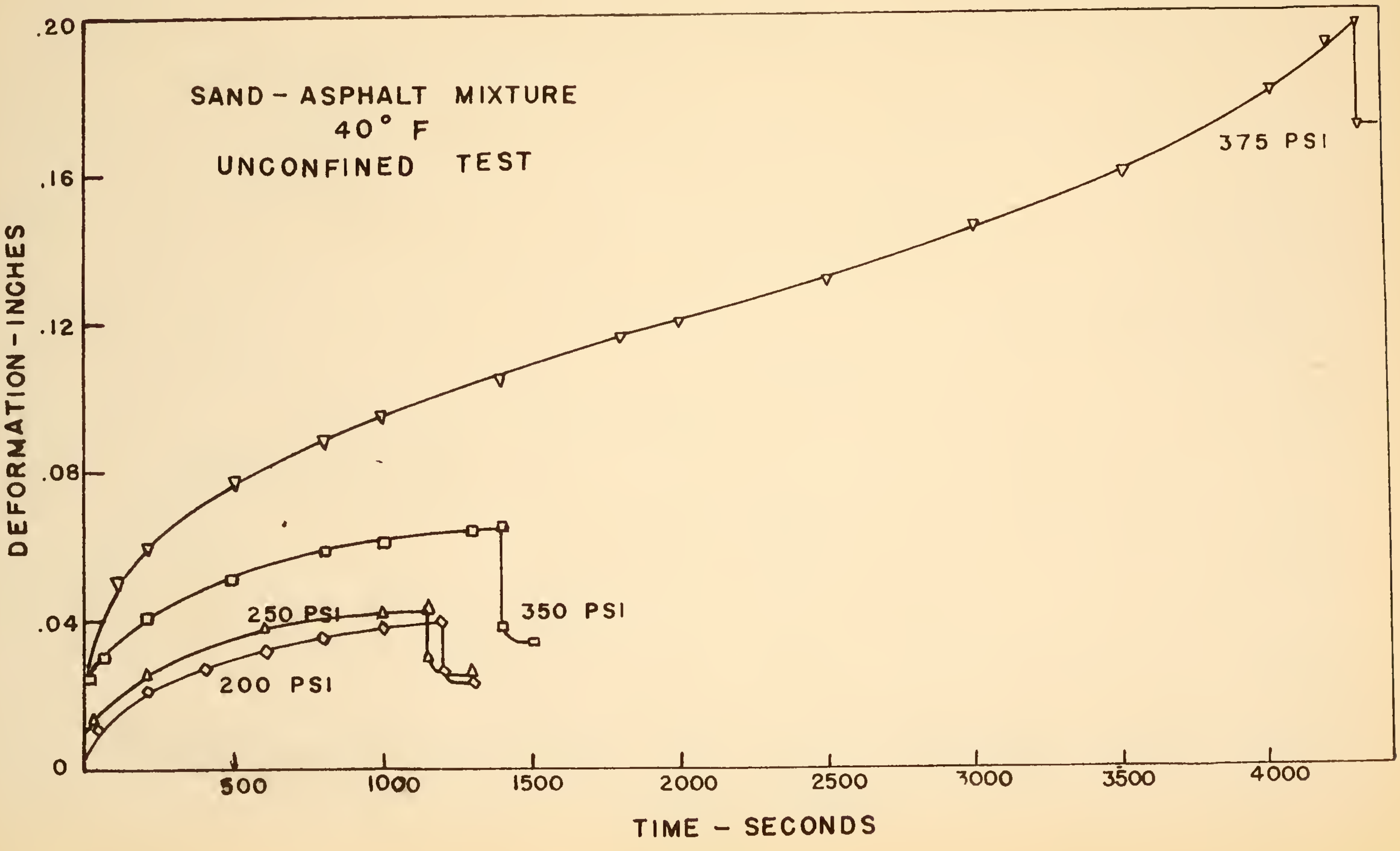

FIGURE 4

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

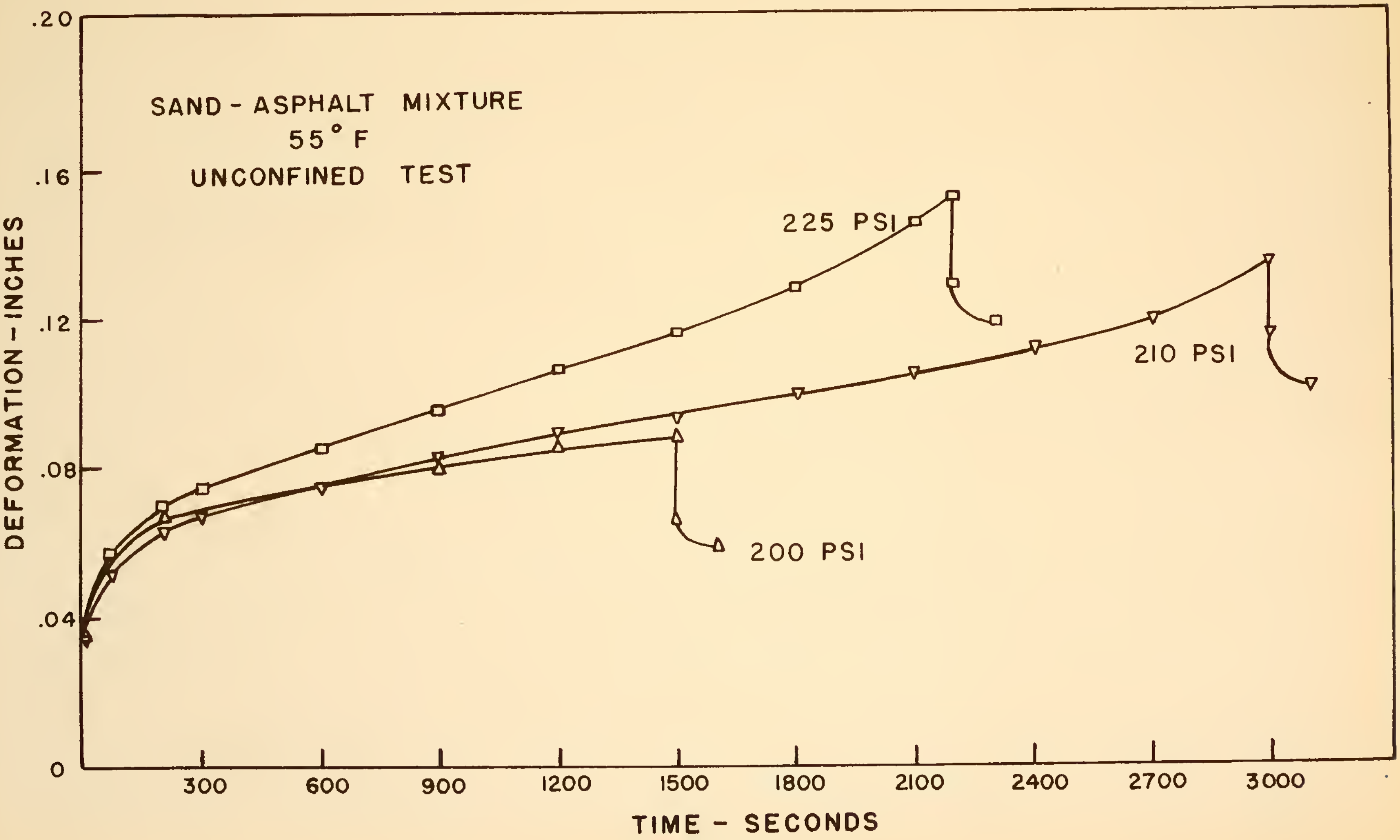

FIGURE 5

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

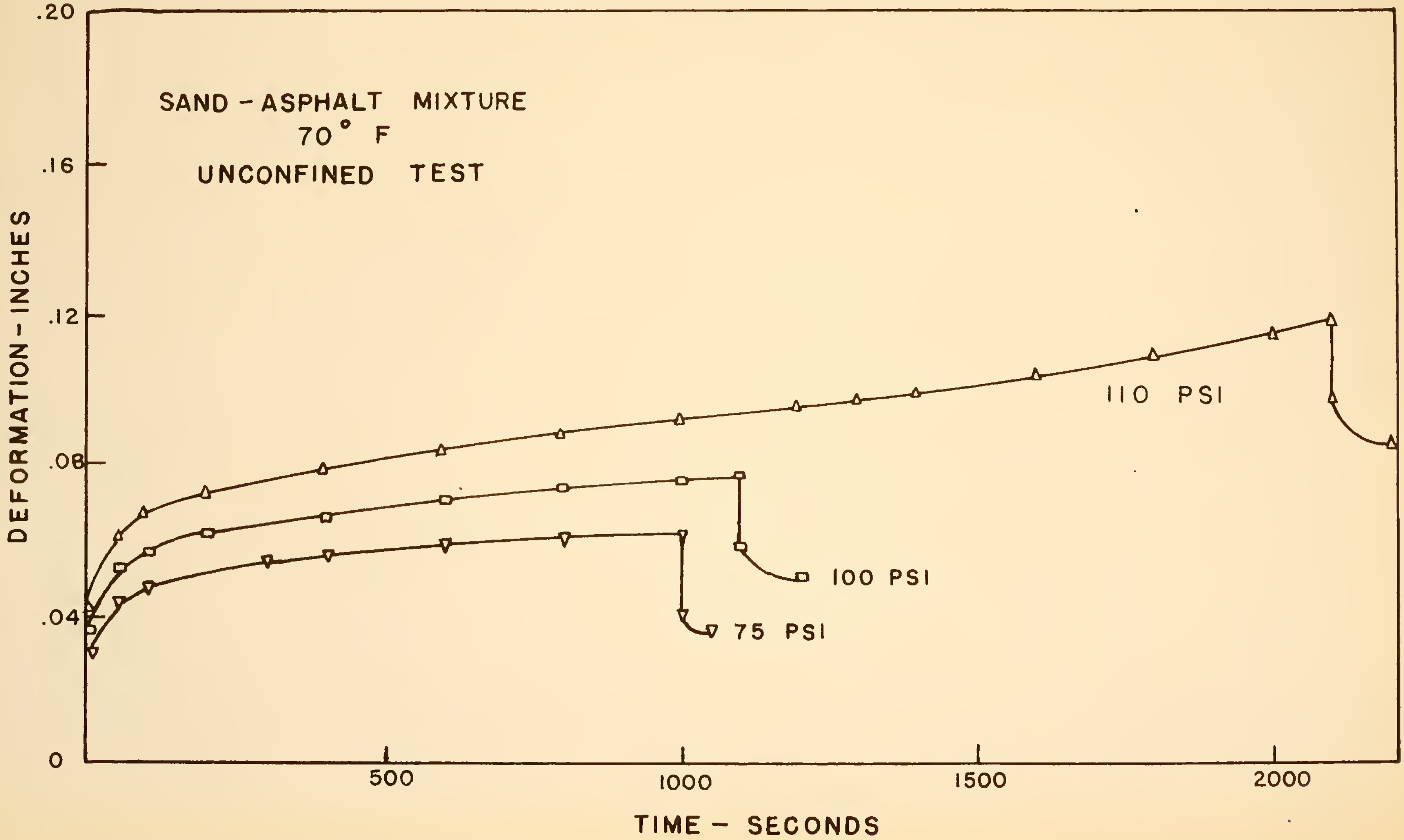

FIGURE 6

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

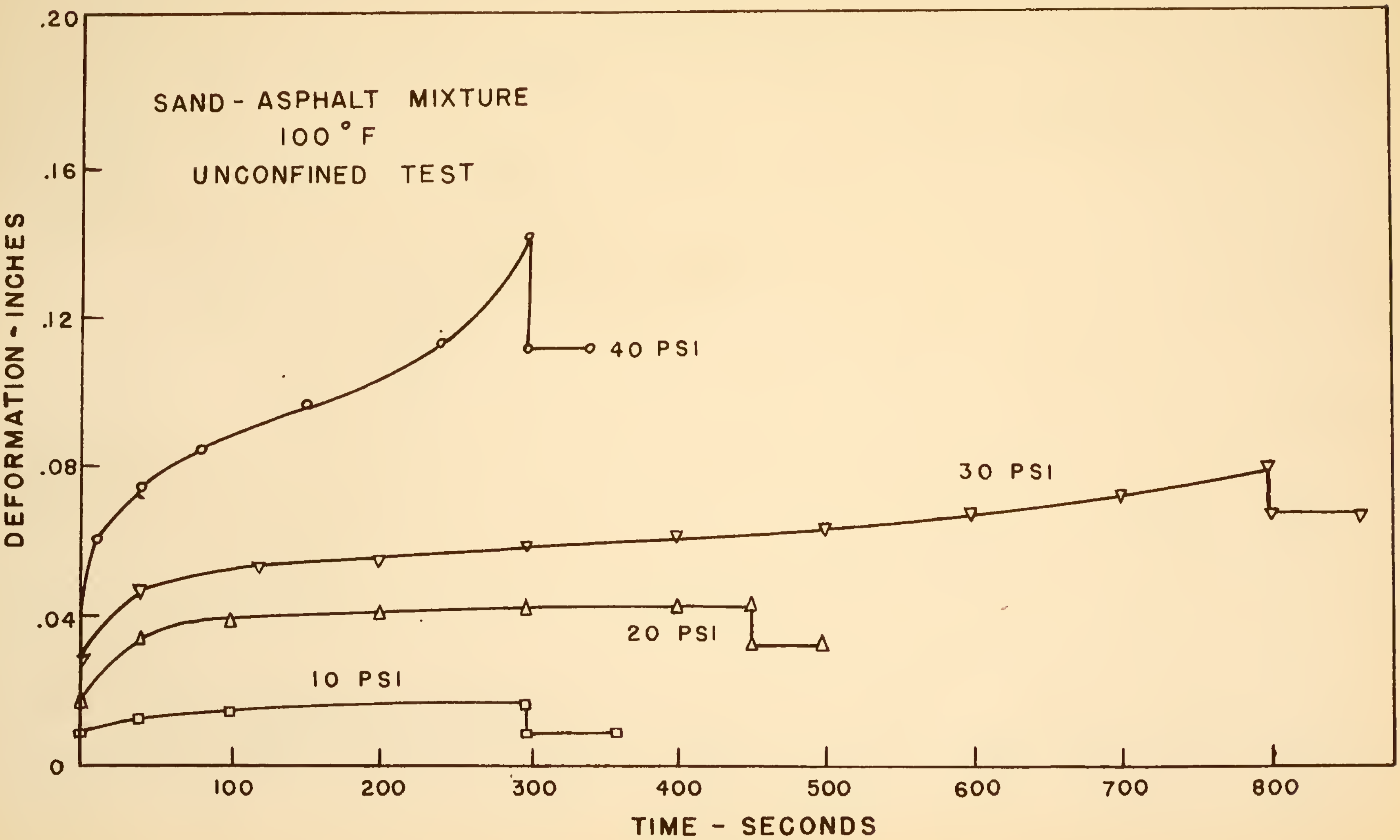

FIGURE 7

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

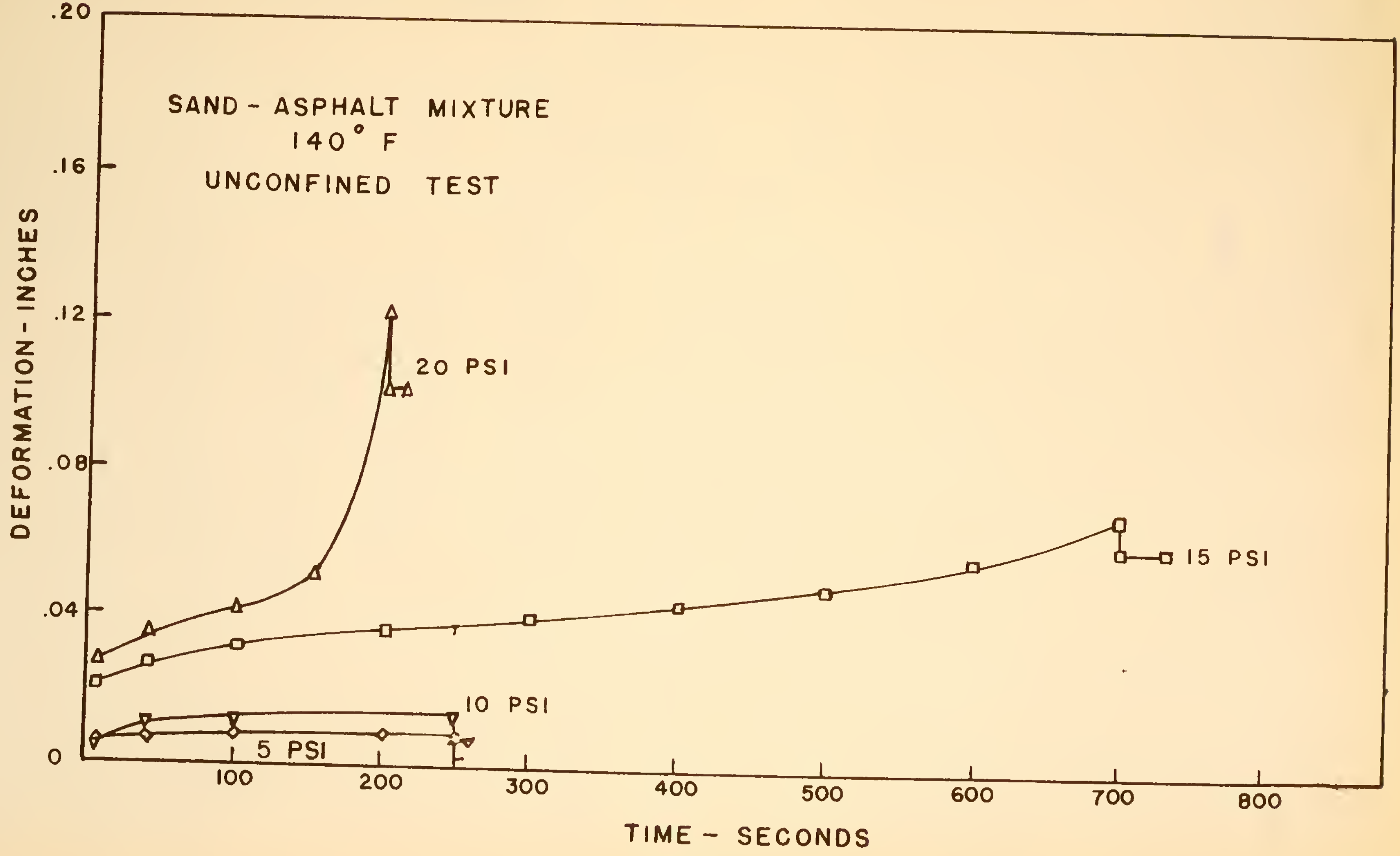

FIGURE 8

deformation followed by continued deformation at a slower rate. Upon removal of the load there is an immediate rebound that occurs which is equal to the instantaneous deformation observed previously. This response to load suggests that the deformation a specimen undergoes should be analyzed in two parts: an elastic or recoverable deformation and a plastic or non-recoverable deformation.

Models proposed by Burgers (10) could be used in part to analyze the time-deformation pattern of a bituminous mixture when subjected to a static load. The models proposed by Burgers consisted of a system of elastic springs and viscous dashpots. In the elastic spring, the applied load produces a deformation or strain which is proportional to the applied stress. Hence:

$$\sigma = R\,\varepsilon_i \qquad (1)$$

where σ = applied stress, psi

ε_i = instantaneous strain, in./in.

R = Modulus of Recovery

This instantaneous strain is completely recovered upon removal of the applied stress.

In the dashpot, an applied load results in a rate of deformation (in./sec.) that is proportional to the applied stress. Hence:

$$\sigma = {}^{\varepsilon v}/_{t} \qquad (2)$$

where σ = applied stress, psi

εv = viscous strain, in./in.

t = time, seconds

γ = mixture viscosity, $\frac{\text{No. sec.}}{\text{in.}^2}$

There are two possibilities of combining the elastic spring and the viscous dashpot; they can be coupled in either series or parallel. If the two elements are coupled in series the force acting in them will be the same and equal to the applied load. This model is sometimes referred to as a Maxwell unit. The measured deformation then would be the sum of the defor-

mations of the individual elements. Applications of a load to this type of model would result in an instantaneous strain followed by deformation in the viscous dashpot at a rate proportional to the applied stress. When the stress is removed the model would rebound an amount equal to the instantaneous strain.

If the elastic spring and viscous dashpot are coupled in parallel their deformation under load must be the same or

$$\varepsilon_T = \varepsilon_E = \varepsilon_V$$

where ε_T = total strain, in./in.

ε_E = elastic strain, in./in.

ε_V = viscous strain, in./in.

This model is sometimes referred to as a Kelvin unit. The load acting on the model distributes itself between the elastic spring and the viscous dashpot. When the load is first applied there is no instantaneous strain but deformation does proceed as a function of time. The applied load first acts on the viscous dashpot but is gradually transferred to the elastic spring. When the load is removed the process is reversed and the model rebounds to its initial height if given sufficient time.

In discussing models it has been assumed that permanent or viscous strain results from any magnitude of applied load. If plastic materials are to be analyzed in terms of models the concept of a yield limit must be introduced as an additional constant. This can be done by introducing a third element consisting of a weight resting on a plane connected to a spring, with a friction force equal to the yield limit holding the block in place when acted upon by stresses less than the yield limit.

Most materials exhibit such a complex pattern that simple models such as the previously described Maxwell or Kelvin unit cannot describe the deformation-time relationship. It is then necessary to approximate this relationship by coupling more than two basic elements or by coupling several

Maxwell units or Kelvin units. This leads to a mechanical model described by Burgers which consists of a Maxwell unit and a Kelvin unit coupled in series. This model, under load, shows a similar deformation-time pattern to a bituminous mixture; however, to approximate closely the action of a bituminous mixture under load would require a much more complicated model than the Burgers model.

It becomes very difficult to describe these more complicated models with a mathematical analysis. A simplification would be to analyze a bituminous mixture under load from the standpoint of its two basic characteristics, its instantaneous elastic strain or rebound shown by equation (1) and its viscous character shown by the equation (2). The analysis of the data collected in this investigation is handled in this manner. From equation (1) for each time-deformation curve the rebound or elastic strain in in./in. is divided into the applied stress. This gives a factor which is called the Modulus of Recovery (R). The values for the Modulus of Recovery for each of the applied stresses at the various temperatures are presented in Table 4.

To obtain a measure of the viscous character of the sand-asphalt mixture, equation (2) was used. The slope of each time-deformation curve was determined in the region of the curve where the deformation rate was constant over a period of time. The reciprocal of this slope when converted to sec./in./in. and multiplied by the applied stress gives a factor which is called Mixture Viscosity (γ). The values of the Mixture Viscosity for each of the applied stresses at the various temperatures is presented in Table 5.

From the data presented in Tables 4 and 5 it can be said that, within the limits of experimental error, the Modulus of Recovery (R) and the Mixture Viscosity (γ) are independent of the applied stress. This fact tends to make the two factors Modulus of Recovery (R) and the Mixture Viscosity (γ)

TABLE 4

The Modulus of Recovery (R) Values for Each Applied Stress at the Various Temperatures

Temperature, °F	Applied Stress, psi	R, psi/in./in.	R (Avg.)
	200	61,538	63,000
	250	83,333	
40	350	51,852	
	375	50,000	
	200	36,363	
55	210	32,324	33,500
	225	36,734	
	75	14,458	
70	100	21,000	17,000
	110	15,714	
	10	57,000	
100	20	8,000	8,200
	30	10,900	
	5	2,105	
140	10	5,714	4,180
	15	4,615	
	20	5,000	

TABLE 5

Mixture Viscosity (γ) for each of the Applied Stresses at the Various Temperatures

Temperature, °F	Applied Stress, psi	γ, $\frac{\#\ sec.}{in.^2}$	γ (Avg.)
	200	1.00×10^7	
40	250	1.185×10^7	1.702×10^7
	350	1.606×10^7	
	375	1.312×10^7	
	200	9.6×10^6	
55	210	9.19×10^6	8.34×10^6
	225	6.25×10^6	
	75	4.22×10^6	
70	100	4.75×10^6	4.64×10^6
	110	4.9×10^6	
100	10	5.0×10^5	
	20	8.5×10^5	7.02×10^5
	30	9.4×10^5	
140	5	3.75×10^5	
	10	5.3×10^5	3.33×10^5
	15	2.8×10^5	
	20	1.4×10^5	

important mixture parameters that may be used in understanding the action of a bituminous mixture under load.

Effect of Temperature Upon Modulus of Recovery and Mixture Viscosity

Since the Modulus of Recovery and the Mixture Viscosity appear to be important mixture parameters, it would be worthwhile to consider the effect of temperature upon these factors. The data of Table 4 are graphically presented in Figure 9 where the log log of the Modulus of Recovery is plotted against the temperature in degrees Fahrenheit. A straight line results, the slope of which may be used as a measure of the effect of temperature upon the Modulus of Recovery. For any one temperature it is not important that the mixture exhibit a high value for a Modulus of Recovery. This results from the fact that, for a given applied stress, the mixture with the lower Modulus of Recovery will exhibit the greater elastic strain and thus will be more capable of adjusting under load without shear failure. Also, it would be desirable to have the Modulus of Recovery affected as little as possible by changes in temperature.

The effects of temperature upon Mixture Viscosity are shown in Table 5 and are depicted graphically in Figure 10 where the log log of the Mixture Viscosity is poises is plotted versus the temperature in degrees Fahrenheit. This type of plot results in a straight-line relationship. The slope of this line may be used as a measure of the effect of temperature upon the Mixture Viscosity. Also plotted in Figure 10 is the log log of the viscosity of the asphalt cement in poises versus the temperature. This relationship, too, is linear. It can be seen that the effects of temperature are greatly reduced for the sand-asphalt mixture over that of the asphalt cement.

RELATIONSHIP BETWEEN TEMPERATURE AND MODULUS OF RECOVERY FOR THE SAND-ASPHALT MIXTURE

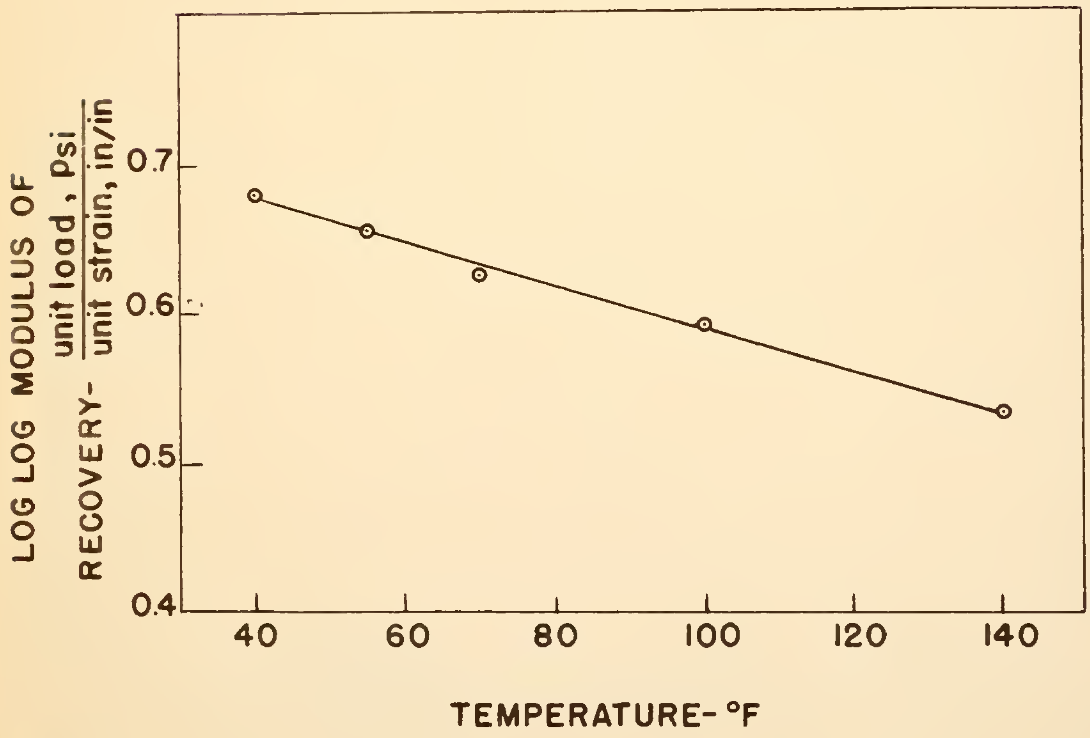

FIGURE 9

RELATIONSHIP BETWEEN TEMPERATURE AND VISCOSITY FOR THE SAND ASPHALT MIXTURE AND THE CONTAINED ASPHALT CEMENT

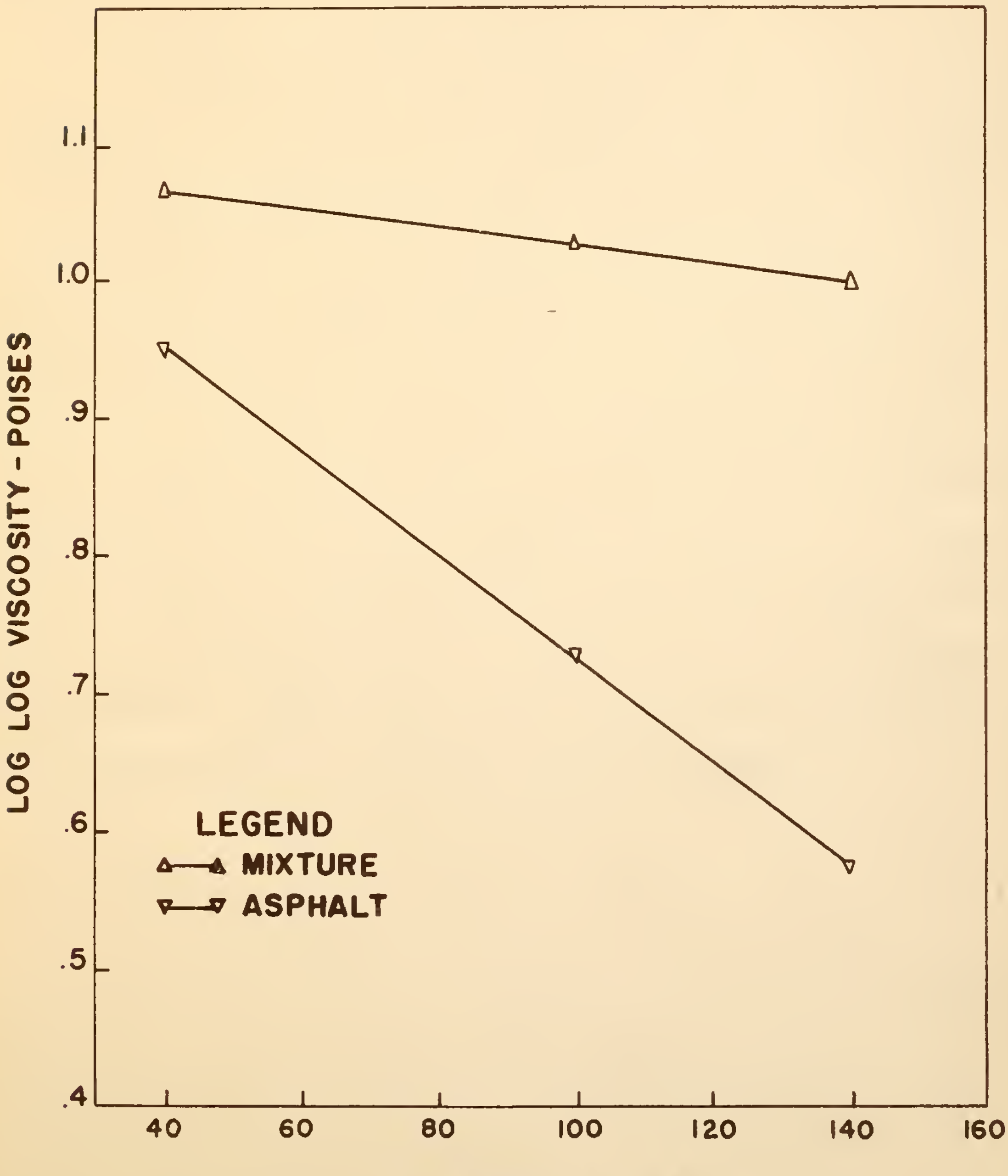

FIGURE 10

For ideal performance in a pavement a bituminous mixture should not possess a high Mixture Viscosity. This results from the fact that it is desirable for the mixture to adjust quickly to applied loads, dissipate the induced stresses rapidly, and hereby prevent excessive stresses from developing in the pavement layer. Mack (6) stated that "low resistance to flow appears to be in contradiction to the requirement of high stability, especially against static loads. This disadvantage can be overcome by proper grading of aggregate and the use of crushed stone."

In Figure 11 the relationship between the viscosity of the sand-asphalt mixture and the viscosity of the contained asphalt cement is shown by plotting log log viscosity of the sand-asphalt mixture in poises versus the log log viscosity of the asphalt cement. This line should be representative of a family of lines. This family of lines would result from the inclusion of other variables in the study such as particle shape, surface texture, gradation and - most important - per cent asphalt and hardness of asphalt. At lower temperatures the viscosity of the mixture is affected only slightly by introducing other variables. This family of lines would, in general, revolve around the low temperature point (40°F for this study) with varying slopes. The limiting condition in any case would be depicted by the dashed line in Figure 11 which represents the situation where the log log viscosity of the mixture equals the log log viscosity of the binder.

RELATIONSHIP BETWEEN VISCOSITY OF THE SAND-ASPHALT MIXTURE AND THE VISCOSITY OF THE CONTAINED ASPHALT CEMENT

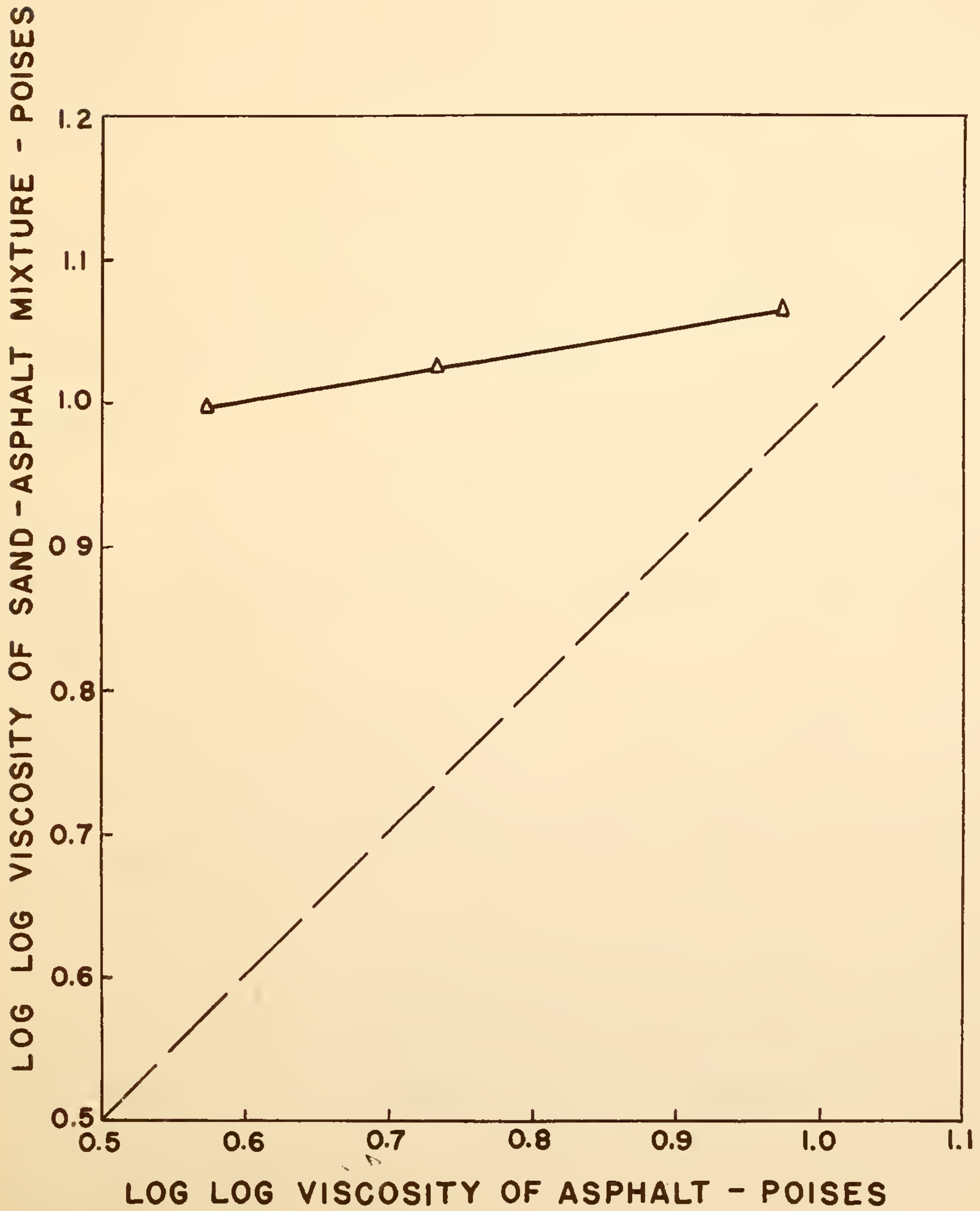

FIGURE 11

SUMMARY OF RESULTS

This was a laboratory study conducted on a specific sand-asphalt mixture which was more plastic in character than many bituminous concretes. It was hoped that the results of this investigation would point out important mixture parameters other than stability and voids. The sand-asphalt mixture led to easier molding and more simple testing procedures than would be possible with a bituminous concrete. Nevertheless, the findings based upon the sand-asphalt mixture should be valid when utilized in a study on bituminous concrete. With these limitations in mind the following summary of results is presented:

1. The Modulus of Recovery and Mixture Viscosity appear to be important mixture parameters worthy of further consideration.

2. In order to prevent excessive stresses from developing when a flexible pavement is strained, a mixture should not exhibit a large Modulus of Recovery.

3. A high value of Mixture Viscosity is not desirable in a bituminous mixture since it will prevent the rapid dissipation of induced stresses and thus allow the development of excessive stresses in the pavement layer.

4. For the range of variables used in the study, plots of log log Modulus of Recovery and log log Mixture Viscosity versus temperature give a simple means of evaluating the effect of temperature upon these two mixture parameters.

5. A plot of log log viscosity of the asphalt versus the log log Mixture Viscosity gives a convenient means of showing the effects of asphalt viscosity upon the viscous nature of the sand-asphalt mixture.

Further work of the type performed in this study, that includes such variables as hardness and amount of asphalt in a mixture, would develop in more detail the relationship between asphalt viscosity and the viscous nature of bituminous mixtures.

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